The Observation of Spin-Polarized Wavevectors spanning the Fermi Surface of Magnetic Nanostructures

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ABSTRACT

We report angle-resolved photoemission measurements of changes in the electronic structure with changing composition of pseudomorphic films of FeNi magnetic alloys grown epitaxially on Cu(001). The measurements show that the sp-band is a prominent feature of the Fermi surface throughout k-space for all of the alloys and the magnetic 3d pseudomorphic fcc films. A band-structure calculation of Ni allows us to identify d-hole pockets which increase in size with changing stoichiometry. Minority spin states highlite specific regions of k-space associated with key spanning vectors that determine the oscillatory exchange coupling which underpins the giant magnetoresistance (GMR) effect in heterostructures.

INTRODUCTION

The exchange coupling between ferromagnetic layers across a nonmagnetic interlayer has attracted much attention and has been observed in numerous systems [1]. The magnetization vectors M oscillate between parallel and antiparallel ordering between the magnetic layers depending on the thickness of the intervening non-magnetic metallic interlayer [2]. This oscillatory behavior of the interlayer exchange coupling can be understood in terms of Ruderman-Kittel-Kasuya-Yosida (RKKY) oscillations in the electronic density, which predicts the different oscillation periods originating from extremal spanning vectors of the Fermi surface of the spacer material [3-5]. In the case of copper spacer heterostructures, spanning vectors have been identified with particular wavevectors spanning particular regions of the "dogbone" structure of the Fermi surface formed by the (sp) states. A "long period" oscillation is observed corresponding to a wavevector spanning the midpoints of the "dogbone" [6]. A shorter period oscillation is occasionally observed in ultrasmooth films associated with the longer k-vector spanning the ends of the "dogbone"], as shown in Figure 1. However, it is not at all clear why this particular periodicity should be prevalent, and so similar for different metallic heterostructures [2]. It has been debated whether the spin-polarization necessary to couple the magnetic films through the non-magnetic layer is carried exclusively by the sp-electrons and the extent the 3d states play a role [7].

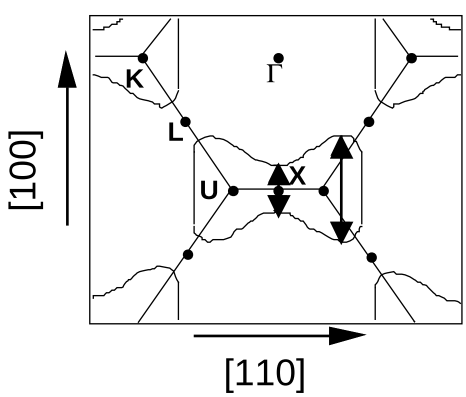

Figure 1. Calculation of the Cu Fermi surface in the (110) plane using the Slater-Koster (SK) method as an interpolation scheme. The bold arrows indicate the short- and longwave spanning vectors thought to be responsible for the oscillatory exchange coupling in magnetic heterostructures.

RESULTS AND DISCUSSION

Fixed electron energy contour maps in k-space were obtained by fixing the detectorís energy window at the Fermi level and rotating the sample. In our experiment, the polar angle was kept constant in the (110) plane. Changing the photon energy in steps of ~5eV from 75-205 eV, we accessed states located at the Fermi level for the high index planes of the fcc Brillouin zone. Assuming free electron final states, and knowing the angle and energy, the measured intensities can be assigned a definite location in k-space [8].

Figure 2 shows the detailed mapping of these states at the Fermi level in the (110) plane of pure Ni and some FeNi alloy films together with their locations in extended (Brillouin) zone space. An intense bright band connecting the L points in the Brillouin zone, observable in all these 3d materials, derives from the sp-band The “dogbone” structure about the X-point is clearly visible. Across the “neck” of this “dogbone” feature, we observe the intensity is influenced due to contributions from d-bands crossing the Fermi level at this position in k-space, their number increasing with increasing number of holes. In particular, the minority-spin d-band in Ni emerges across the neck of this dogbone. This enhances electron scattering between (mainly minority) d and sp-states in this particular region of k-space. With increasing hole concentration, we see a concentration of intensity in these regions of k space, as well as at the centre of the Brillouin zone, (Γ-point).

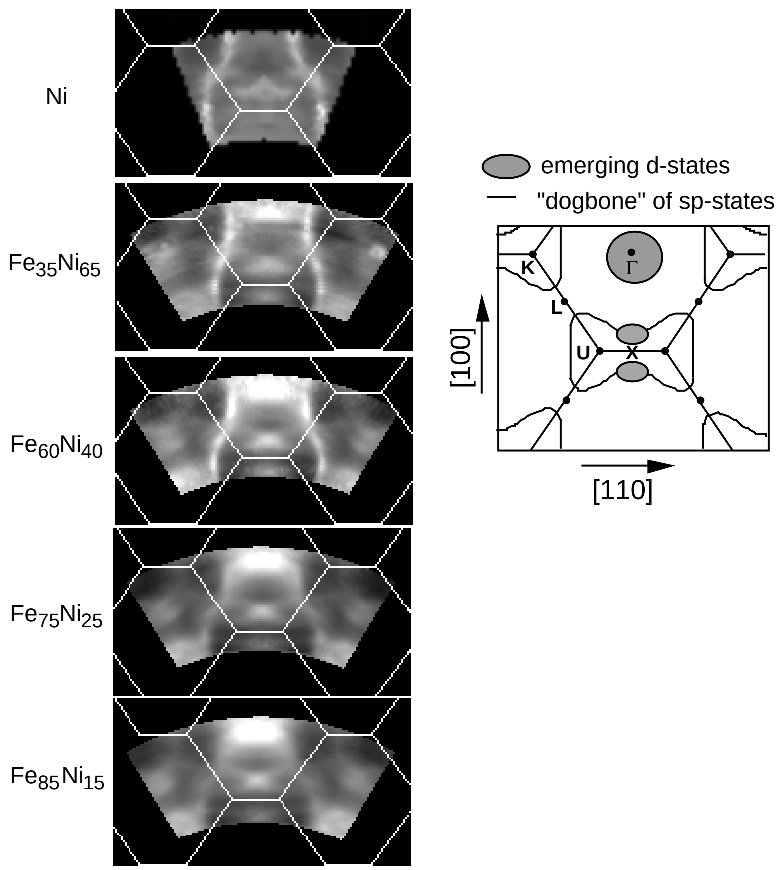

Figure 2. Photoemission reciprocal-space distribution of states at the Fermi energy in the (110) plane of fcc crystalline films of Ni and NiFe alloys. The inset is a schematic showing the "dog-bone shape" of the sp-states, and "hotspot" regions where minority-spin d-states emerge.

In summary, we have mapped states in momentum space at the Fermi energy using a range of photon energies in angle-resolved photoemission for a series of magnetic transition metals as well as for their binary alloys as a function of stoichiometry. These alloys possess the same crystallographic structure as that of the Cu(100) substrate when grown as ultrathin epitaxial layers. This implies that the position of the Fermi level is a direct reflection of the hole concentration in the d-bands, which we can vary by either changing the elemental material or by alloying the various elements. This is why we expect the Fermi surface maps in k-space to evolve gradually with alloy stoichiometry.

As a result, we see sharply defined sp-states throughout k-space characterized by the same “dogbone” Fermi surface “hole” structure characteristic the <110> projection of fcc copper. Emptying the d-bands leads to states appearing localized in the dogbone region and as a diffuse region about the zone center. Mixing of d- and sp-states, mainly of minority spin polarization, in regions of k-space identified previously with the locations of spanning wavevectors are driving minority-spin RKKY Fermi surface oscillations which couple magnetic layers separated by nonmagnetic fcc spacer films in spin-valve heterostructures showing GMR oscillations. The observation of a similar shaped sp feature in all these fcc pseudomorphs could explain the why the long-wavelength oscillations are similar in all the fcc heterostructures.

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